

TIME-DEPENDENT DISTINGUISHABILITY: CHOOSING TO BE A WAVE OR A PARTICLE

T.P. Grayson, X.Y. Zou, D. Branning, J.R. Torgerson and L. Mandel

Department of Physics and Astronomy, University of Rochester, Rochester, NY 14627

Abstract

Interference experiments with connected parametric down-converters have demonstrated that the possibility, in principle, of identifying the photon path through the interferometer is sufficient to wipe out all interference, irrespective of whether the identification is actually made. The distinguishability of the photon path can be controlled by a time-dependent shutter, which leaves the choice whether the photon behaves as a wave or as a particle in the experimenter's hands. By contrast, in some more recent experiments involving the addition of a low-Q cavity, each idler photon makes the choice whether the associated signal photon behaves like a wave and exhibits interference, or like a particle.

1 Introduction

In this paper we briefly review some recent interference experiments in which several non-classical and non-local effects show up. The basis for all the experiments is the process in non-linear optics known as parametric down-conversion that generates pairs of signal and idler photons simultaneously in an entangled quantum state [1, 2]. The experiments outlined below all make use of two down-converters, and the prototype of the arrangement is illustrated in Fig.1 [3, 4].

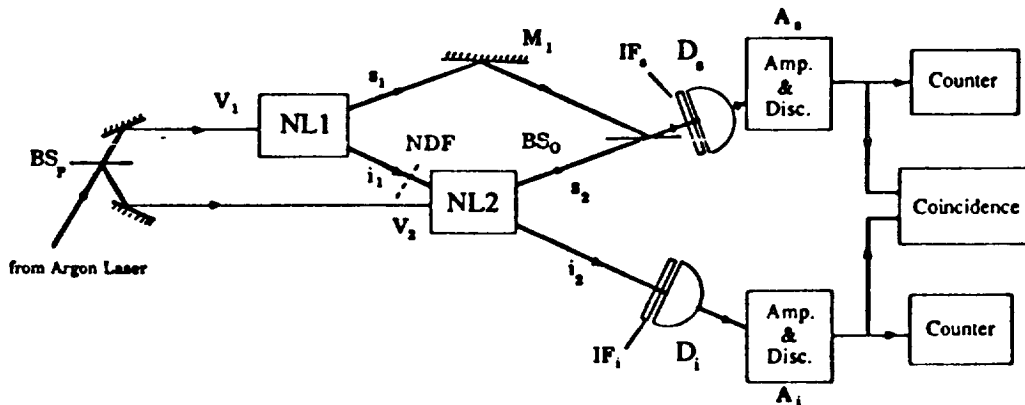


Fig. 1. Outline of the experimental set-up underlying all the experiments [Reproduced from Zou et al (1991)].

Here $NL1$ and $NL2$ are two similar crystals with a $\chi^{(2)}$ non-linear susceptibility functioning as down-converters. Both crystals are optically pumped by mutually coherent light beams of

amplitudes V_1, V_2 derived from the same laser beam. As a result down-conversion can occur at $NL1$ with the emission of a signal s_1 and an idler i_1 photon simultaneously, or down-conversion can occur at $NL2$ with the emission of a pair of s_2, i_2 photons. The crystals are so oriented that i_1 passes through $NL2$ and then is colinear with i_2 . At the same time the s_1 and s_2 beams are brought together at the output beam splitter BS_o where they are mixed, and the mixed signal beams fall on signal detector D_s . We are interested to know whether s_1 and s_2 exhibit mutual coherence and interfere. If they do, then the photon counting rate of D_s will oscillate as BS_o is slowly translated in a direction perpendicular to its face.

The results of the experiment are illustrated in Fig 2. [3]. It appear that s_1 and s_2 do indeed

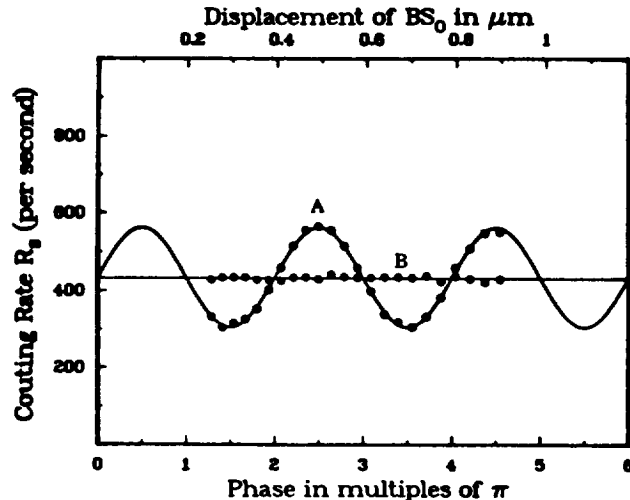


Fig. 2. Experimental Results of the Interference Experiment [Reproduced from Zou et al (1991)].

interfere (curve A) when i_1 and i_2 are aligned, but that all interference disappears when i_1 is blocked by a beam stop (curve B). The average rate of photon emission is, however, the same in both cases. If we argue that i_1 induces coherence between s_1 and s_2 in some sense, then this induced coherence is unusual because it is not accompanied by any induced emission. If, instead of blocking i_1 , we insert a filter NDF in the path of i_1 , as shown in fig 1, then the resulting interference pattern of s_1, s_2 is found to have a visibility proportional to the absolute transmissivity $\mathcal{T}$ of the filter. It can be shown that under somewhat idealized conditions, and with equal signal s_1 and s_2 intensities, the degree of coherence $|\gamma_{s_1 s_2}|$ between s_1 and s_2 or the visibility is given by [4]

$$|\gamma_{s_1 s_2}| = |\gamma_{DC}(\tau_0 + \tau_2 - \tau_1)| |\mathcal{T}|, \quad (1)$$

where γ_{DC} is the normalized second order auto-correlation function of the down-converted field. τ_0, τ_2, τ_1 are propagation times from $NL1$ to $NL2$, from $NL2$ to D_s , and from $NL1$ to D_s , respectively and $\tau_0 + \tau_2 - \tau_1 = 0$ when the interferometer is balanced, in which case $\gamma_{DC}(0) = 1$. It is possible to understand the absence of mutual coherence between s_1 and s_2 when i_1 is blocked in terms of the potential distinguishability of the photon sources. With the help of an auxiliary measurement with detector D_i shown in Fig. 1, that does not disturb the interference between s_1 and s_2 , one can determine the source of the detected signal photon [3].

2 Effect of a Differential Time Delay

As is well known, the insertion of a differential time delay $\mathcal{T}_D$ in one interferometer arm generally lowers the visibility, and if $\mathcal{T}_D$ exceeds the coherence time T_c of the light the visibility drops close to zero. But according to Eq. (1), the effect of incrementing τ_2 by τ_D should be exactly the same as the effect of leaving τ_2 unchanged and incrementing τ_0 instead, even though τ_0 relates to the i_1 path which is not really part of the interferometer. The reason is the quantum entanglement of signal and idler photons, which makes the effect of a delay on the signal virtually indistinguishable from the effect of the same delay on the idler. As the experimental results shown in Fig. 3 indicate, the observed visibility falls with increasing τ_D in accordance with Eq. (1), although it is the idler 1 which is being delayed [5].

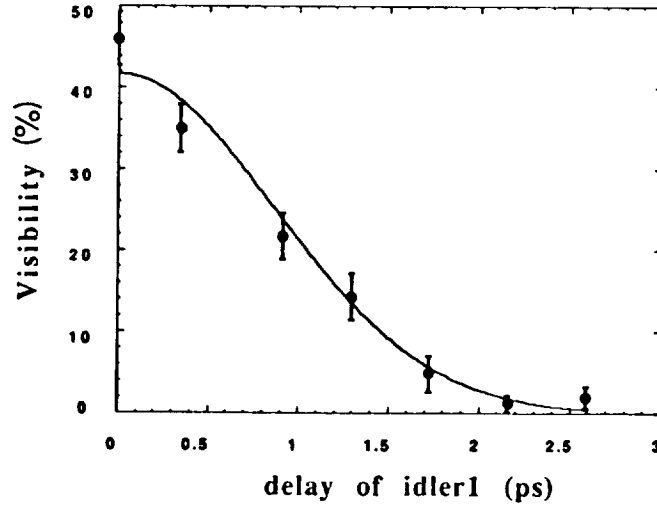


Fig. 3. Experiment Results showing the effect of a time delay imposed on the i_1 idler photons [Reproduced from Zou et al (1993)].

3 Effect of a Time-Dependent Filter

So far we have dealt only with steady state situations. An interesting variant of the foregoing arises if the filter of transmissivity $\mathcal{T}(t)$ shown in Fig. 1 is allowed to vary in time. Indeed we may think of the filter as a time-dependent shutter that opens and closes at certain times. We now ask how the transmissivity affects the visibility of the interference contributed by a signal photon which is detected by D_s at time t .

This problem has recently been examined theoretically [6]. With the help of a spectral analysis of the fields and the filter response function it was shown that the visibility of a signal photon detected by D_s at time t is completely determined by the filter transmissivity $\mathcal{T}$ at the earlier time $t - \tau_2 - \tau_0''$. Here τ_0'' is the propagation time of photons from the filter to $NL2$. The time $t - \tau_2 - \tau_0''$ is therefore the time at which a photon from $NL1$ on the way to $NL2$ and then on to D_s would have passed the filter. Of course there is no such photon. But the time $t - \tau_2 - \tau_0''$ is the time when i_1 would pass the filter if the photons originate in $NL1$. Provided the filter is then open ($\mathcal{T} = 1$) this photon is indistinguishable from an i_2 photon from $NL2$. It does not matter at all what the transmissivity is at any other time.

4 Effect of a Resonant Cavity around the Idler Beams

Consider the experimental arrangement shown in Fig. 4 [7]. Here a beam splitter BS_i has been inserted in the i_1 beam between $NL1$ and $NL2$, and light reflected from BS_i is detected by an additional detector D_i such that the propagation time from $NL1$ to D_i is also τ_1 . It follows that an s_1, i_1 photon pair emitted by $NL1$, of which the i_1 photon is reflected by BS_i and passed to D_i , will result in coincident detections by both D_s and D_i . Needless to say, these photons do not contribute to the signal interference because their source is known. Mirrors $M3, M4$ are introduced so as to form an optical cavity resonant with the idlers. An i_1 photon which is transmitted through BS_i may then propagate to $M4$, where it may be reflected and again pass through BS_i ; it may then be reflected from $M3$ and return to BS_i , where it is reflected and passed to D_i . Similarly, an i_2 photon emitted from $NL2$ may traverse the cavity and end up being reflected by BS_i and detected by D_i . Needless to say, an i_1 or i_2 photon which has made one or more trips around the cavity in this way will be detected by D_i later than the conjugate signal photon is detected by D_s . Moreover, if the interferometer is balanced, the time delay between detections by D_i and D_s will be the same whether the photons originate in $NL1$ or $NL2$. As a result the sources of these photons are indistinguishable and interference is to be expected, whereas the sources are distinguishable for coincident signal-idler detections.

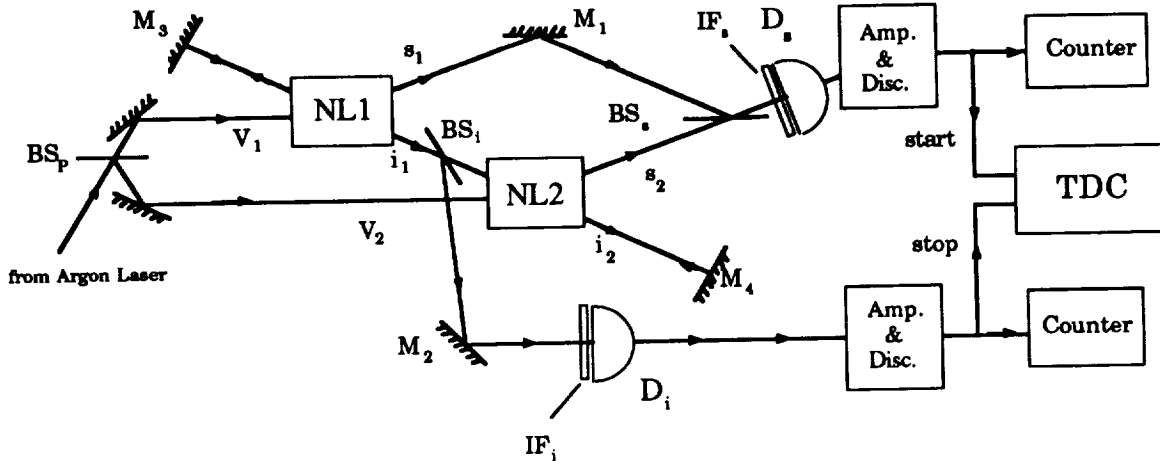


Fig. 4. Outline of the experiment with a resonant idler cavity [Reproduced from Grayson et al (1993)].

In order to measure the delay time intervals τ_D between D_s and D_i detections the photoelectric pulses from D_s and D_i are passed to the 'start' and the 'stop' inputs of a time-to-digital converter (TDC) that measures and digitizes the intervals and accumulates the data in channels determined by τ_D . The number of events accumulated in delay channel τ_D is then a measure of how many photon pairs have a time separation τ_D . In addition by varying the optical path difference through displacement of BS_o we can extract the visibility of the interference pattern formed by the two signal beams.

The results of the experiment together with theoretically expected values are shown in Fig. 5. [7]. Fig. 5a gives the accumulation of photon pairs as a function of the delay τ_D . The peak centered at $\tau_D = 0$ corresponds to idler i_1 photons that emerge from the optical cavity without

making any round trip. The observed visibility is shown in Fig. 5b. Those photons that emerge without extra delay are counted but exhibit no interference, because they originate in NL1. Those photons that emerge after one cavity roundtrip behave like waves and interfere with about 50% visibility.

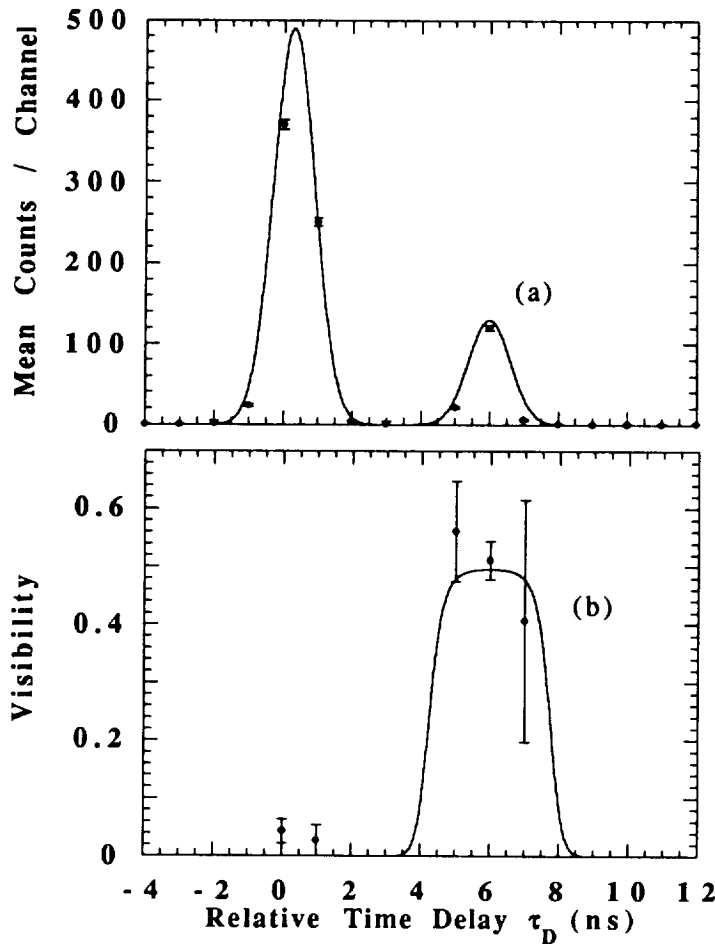


Fig. 5. Experimental results showing how the photon pair rate and the visibility vary with the delay τ_D . The cavity round trip time is 6 nsec. [Reproduced from Grayson et al (1993)]

Because the idlers are registered by the *TDC* after the signal photons, the experiment has some of the character of a delayed choice experiment. But the 'choice' is here made not by the experimenter but by the idler photons. Those idlers that are reflected by BS_i at the first encounter cause the conjugate signal photons to behave like particles; those idlers that make one round trip before emerging from the cavity cause the conjugate signal photons to behave like waves and to interfere. We note that both aspects of nature are here exhibited by different photons in the same apparatus.

5 Acknowledgments

This research was supported by the National Science Foundation and by the U.S. Office of Naval Research.

References

- [1] D.N. Klyshdo, Zh. Eksp. Teor. Fiz. **55**,1006 (1968) [Sov. Phys. JETP **28**, 522 (1969)].
- [2] D.C. Burnham and D.L. Weinberg, Phys. Rev. Lett. **25**, 84 (1970).
- [3] X.Y. Zou, L.J. Wang and L. Mandel, Phys. Rev. Lett. **67**, 318 (1991).
- [4] L.J. Wang, X.Y. Zou and L. Mandel, Phys. Rev. A **44**, 4614 (1991).
- [5] X.Y. Zou, T.P. Grayson, G.A. Barbosa and L. Mandel, Phys. Rev A **47**, 2293 (1993).
- [6] L.J. Wang, X.Y. Zou and L. Mandel, J. Opt. Soc. Am B **9**, 605 (1992).
- [7] T.P. Grayson, X.Y. Zou, D. Branning, J.R. Torgerson and L. Mandel, to be published (1993).